Pulsations of auroral kilometric radiation at Pc1 frequencies

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[1] Cases of AKR pulsations at frequencies 1 to 4 Hz, typical for Pc1 geomagnetic pulsations, were observed from four Cluster spacecraft. 15 events were found in years 2001–2005, with 14 occurring in a recovery phase of a strong magnetic storm. In a studied event of 22 June 2003 the AKR pulses show positive frequency drifts, corresponding to the earthward motion of AKR sources along auroral magnetic field lines. The source velocities match calculated propagation of shear Alfvén waves within the auroral cavity. In our scenario a primary cause of the AKR Pc1 pulsations can be inertial Alfvén waves converted either from electromagnetic ion cyclotron waves generated in the equatorial magnetosphere, or from electromagnetic ion cyclotron waves generated in the auroral cavity. We suggest that the parallel electric field of the earthward propagating wave can periodically produce the 'shell' electron distribution, which could be the free energy source of the AKR pulse emission through the electron-cyclotron maser instability. **Citation:** Hanasz, J., R. Schreiber, J. Pickett, and H. de Feraudy (2008), Pulsations of auroral kilometric radiation at Pc1 frequencies, *Geophys. Res. Lett.*, *35*, L15819, doi:10.1029/2008GL034609.

1. Introduction

[2] Auroral Kilometric Radiation (AKR) is a strong and extremely variable radio emission generated in the auroral magnetosphere at a frequency near the gyro-frequency of electrons [*Benson and Calvert*, 1979] in the range from 30 to 900 kHz, corresponding to source altitudes from 18,000 to 2000 km. The electron cyclotron maser instability proposed by *Wu and Lee* [1979], driven by an unstable 'shell' [*Ergun et al.*, 2000] electron distribution is most likely the mechanism responsible for this emission. Two possible drivers leading to formation of unstable electron distributions producing AKR have already been discussed. First: Quasi-steady parallel electric fields accelerate electrons downward in the upward current region, as concluded from FAST observations [*Ergun et al.*, 2000]. The 'typical' AKR is therefore believed to be driven by the quasi-steady parallel electric fields [*Su et al.*, 2007]. Second: Parallel electric fields of inertial Alfvén waves propagate earthward along auroral magnetic field lines, as deduced from the fast source expansion observed in broadband AKR bursts [*Hanasz et al.*, 2001; *Janhunen et al.*, 2004]. These fields propagating in the converging magnetic field of the Earth, accelerate electrons downward with fluxes that are modulated at Alfvén wave eigenmode frequencies [*Ergun et al.*, 2006]. The evidence for this is provided by observations of AKR pulsations at frequencies of Pc5 [*Hanasz et al.*, 2006] and Pi2 [*Morioka et al.*, 2007], AKR s-bursts [*Su et al.*, 2007], and electromagnetic ion cyclotron waves observed within a source region of AKR [*Bessho and Menietti*, 2007].

[3] In this paper we present another kind of periodic AKR pulsation. It is observed at frequencies of repetition of 1 to 4 Hz, typical for Pc1 geomagnetic pulsations (0.2–5 Hz). We suggest that the inertial Alfvén waves at Pc1 frequencies play a driving role in generation of these AKR pulsations.

2. Observations

[4] Pulsations of AKR at Pc1 frequencies are a very rare phenomenon. Only 15 examples of AKR pulsations at Pc1 frequencies were found between 1 February 2001 and 31 December 2005 in the data recorded by the Wideband Data (WBD) instrument on board the four Cluster satellites (Table 1). A description of WBD can be found in work by *Gurnett et al.* [1997]. Of all the observed cases, 14 occurred in a recovery phase of a strong magnetic storm on 16 May 2005 in a time interval of 1h 20m beginning at 13h 28m UT. Figure 1 displays an FFT spectrogram of AKR pulsations recorded on 22 June 2003 18 h 46 m UT on the SC4 satellite. We select this event for further case study for its exceptional regularity and clear frequency drifts at frequencies below 70 kHz.

[5] At the time of the event all four Cluster satellites were orbiting in the polar region of the southern hemisphere, the pair SC2 - SC4 at a radial distance of 12 R_E (Earth radii) from the Earth, magnetic local time (MLT) 7 h, and magnetic latitude (MLat) $-71.5°$, and the pair of SC1 - SC3 at a radial distance of 10 R_E, MLT 9 h, and MLat $-80.0°$. Simultaneous spectra of the event obtained from both pairs exhibit practically the same periodic structure, with a slight difference in intensity at low frequencies (not shown). The most characteristic feature of this event is a chain of 15 periodic pulses of AKR recorded in a time interval of 6 seconds (Figure 1). This remote observation of AKR emission covered a frequency range from about 48 to 90 kHz, corresponding to the altitude of the pulsating AKR source of 13,500 to 9,500 km using a dipole approximation of the geomagnetic field. The absence of a signal above 90 kHz is due to a cut-off of the receiver's filter (not shown). Above 70 kHz the frequency drift rates were too large to be measured. In most of the other events the pulsations were limited to higher frequencies, where the drift rates were, as in this case, too large to be measured. The AKR pulsation continued up to 18h 46m 05s UT, though was partly overlapped with a strong 'non-periodic' emission of AKR. Altogether 21 pulses could be identified in a time interval of

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Table 1. Events of AKR Pc1 Pulsations Observed With WBD on Cluster SC4

Date	Start (UT)	Time (s)	F_{puls} (Hz)	MLat (deg)	MLT[a]	Radius R_E
Jun 22, 2003	18:45:56	15	2.7–1.6	−71.5	6:50	12.2
May 16, 2005	13:27:08	5	2.2	−49.4	7:38	14.4
May 16, 2005	13:28:23	3	3.25	−49.4	7:39	14.4
May 16, 2005	13:40:16	12	1.87	−50.2	7:42	14.3
May 16, 2005	13:44:58	66	2.05	−50.5	7:43	14.2
May 16, 2005	13:50:53	2	3.6	−50.9	7:45	14.1
May 16, 2005	13:51:00	12	4.0 − 2.5	−50.9	7:45	14.1
May 16, 2005	13:58:20	4	4.25	−51.4	7:47	14.1
May 16, 2005	13:58:54	3	3.0	−51.5	7:48	14.1
May 16, 2005	13:58:58	6	4.0	−51.5	7:48	14.1
May 16, 2005	14:16:18	10	1.7–1.3	−52.7	7:53	13.9
May 16, 2005	14:16:30	13	2.33	−52.7	7:53	13.9
May 16, 2005	14:44:11	53	2.21	−54.8	8:03	13.5
May 16, 2005	14:48:11	15	1.73	−55.1	8:04	13.5
May 16, 2005	14:48:30	6	1.83	−55.1	8:04	13.5

[a]MLT is given in hours and minutes.

9 s, corresponding to the average pulsation frequency of 2.3 Hz. In other cases the frequency of pulse repetition covered the range from 1.3 to 4.25 Hz, which matches well to Pc1 frequencies. It should be noted that in some other events negative drifts were also observed from time to time.

[6] Wavy lines overlaid on the spectrogram in Figure 1 show AKR pulse intensity profiles averaged over 1 kHz bandwidth (equivalent to 10 successive frequency steps of FFT) in a logarithmic scale. Duration of the average AKR pulse was 0.25 s equal to approximately half a wave cycle of 0.5 s with amplitude of intensity fluctuation of approximately 30 dB (corresponding to $\sim 10^{-11}$ $V^2 m^{-2} Hz^{-1}$). For the average velocity of the AKR source of ~8,000 km/s, and the pulse duration of 0.25 s, the parallel source size will be ~2,000 km, and the parallel wavelength will be ~4,000 km.

[7] The positive frequency drift rates are characteristic for AKR pulses discussed in this letter. The nearly vertical overplotted lines in Figure 1 associated with selected pulses, are quadratic regressions through maxima of pulse intensity. They were numerically differentiated to obtain the pulse frequency drift rates shown in Figure 2a. Assuming the emission at the electron-cyclotron frequency and the AKR source stretched along the dipole magnetic field line of 70° invariant latitude, the positive frequency drift can be interpreted as due to a downward motion of periodic AKR sources along the auroral magnetic field lines, with speeds ranging from 3,000 to 15,000 km/s (average 8,000 km/s). Figure 2b shows apparent AKR source velocities, determined with the above assumptions from the frequency drifts rates represented in Figure 2a. Such velocities can be expected for shear Alfvén waves propagating through the auroral cavity. Similarly, the negative drift rates, which were sporadically observed in some pulsation events, can be interpreted as due to an upward motion of AKR sources with speeds of shear Alfvén waves.

[8] To summarize the observations: Cases of AKR pulsation (the order of 30 dB) at frequencies of 1 to 4 Hz typical for Pc1 geomagnetic pulsations were sporadically observed from all Cluster satellites. In the studied event of 22 June 2003 the AKR pulses show positive frequency drifts, corresponding to the periodic AKR sources formed in the upper part of the auroral cavity moving downward with speeds of 3,000 to 15,000 km/s through the auroral cavity.

3. Discussion

[9] The fast AKR sources, moving with apparent velocities typical for shear Alfvén waves in the auroral cavity, suggest a resonance between the inertial Alfvén waves and the electron velocity distribution. For the cold plasma approximation the wave parameters can be estimated from

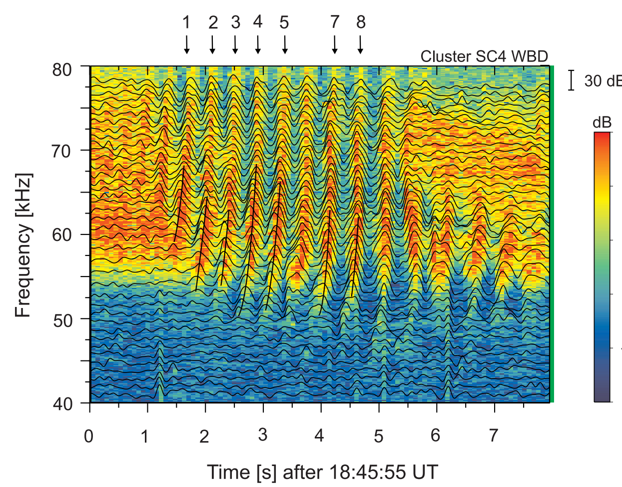

Figure 1. High resolution FFT (2180 points) frequency-time spectrogram of AKR pulsating at the Pc1 frequency, obtained from the SC4 Cluster satellite on 22 June 2003 18h 45m 55s UT. Overlaid are stacked intensity profiles in logarithmic scale, averaged over 1 kHz equivalent to a bandwidth of 10 successive frequency steps of the FFT spectrogram (obtained from 2180 data points). The nearly vertical lines associated with selected pulses are quadratic regressions through maxima of pulse intensity. The numbered pulses are further analyzed in Figure 2. Position of the satellite: distance from the Earth 12 Earth's radii, magnetic local time (MLT) 6.9 h, magnetic latitude −71.5°.

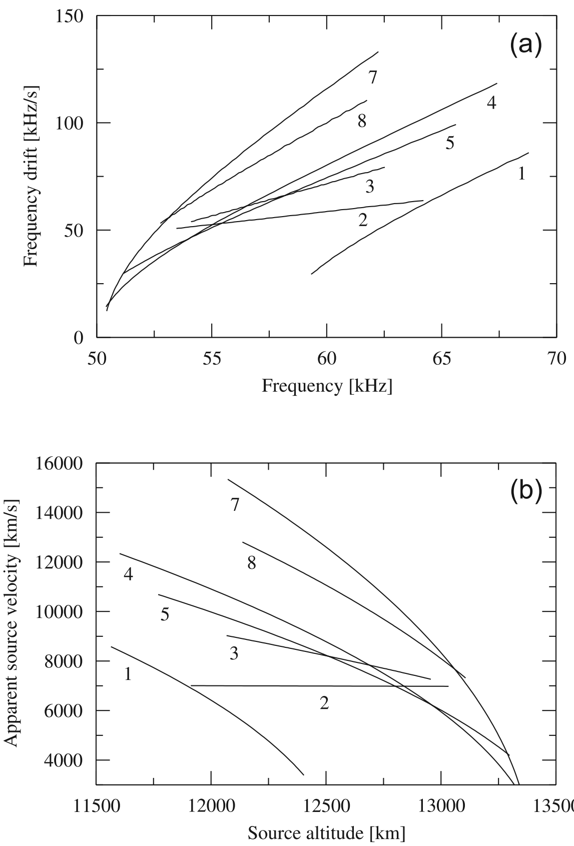

Figure 2. Apparent propagation of pulsating AKR sources. (a) Frequency drift rates calculated by differentiation of the regression curves shown in Figure 1. (b) Parallel velocities of AKR sources determined from frequency drift rates assuming AKR generation at the electron cyclotron frequency, dipole model of the Earth's magnetic field, and AKR source extended along the magnetic field line of 70° invariant latitude.

the dispersion relation for the shear Alfvén waves propagating in the auroral cavity:

$$V_{\|}^2 = \left(\omega/k_{\|}\right)^2 = V_a^2/\left(1 + k_\perp^2 \lambda_e^2\right),$$

where $V_{\|}$ is phase velocity of the wave, ω is angular frequency of the wave, $k_{\|}$ and $k_\perp$ are parallel and perpendicular components of the wave vector, V_a is Alfvén speed, and $\lambda_e = c/\omega_{pe}$ is electron inertial length, c is velocity of light, and ω_{pe} is plasma frequency of electrons. The resonance between the electron velocity distribution and the wave is most effective when their parallel velocities are nearly equal.

[10] For example, let us consider AKR emission generated at a field line of 70° invariant latitude and at an altitude of 12,000 km, where the value of the dipole magnetic field is 0.0224 Gauss and a frequency of AKR emission (assumed to be the electron cyclotron frequency) is 62.7 kHz. The condition for AKR generation, $\omega_{pe}/\omega_{ce} \leq 0.1$ [*Hilgers*, 1992; *Ergun et al.*, 1998] requires reasonable values of 0.5/cm^3 for the electron number density and 7.6 km for the electron inertial length within the auroral cavity. From Figure 2b we determine the range of source speeds from ~6,000 to ~16,000 km/s for the altitude of 12,000 km. With these values the dispersion relation gives the range of the perpendicular wavelength scaled to a level of the ionosphere $\lambda_{ion\perp} = \lambda_\perp (R_E/R)^2$, (where $\lambda_\perp = 2\pi/k_\perp$) from 0.49 km for $V_{\|}$ = 6,000 km to 1.35 km for $V_{\|}$ = 16,000 km. The latter values are compatible with earlier determinations of 2 km by *Swift* [2007], 5 km by *Chaston et al.* [2002], and 1 km by *Lysak and Lotko* [1996].

[11] To our knowledge there are no simultaneous ground-based observations of Pc1 geomagnetic pulsations in the southern hemisphere for this case. Available observations from the northern hemisphere (Scandinavian chain of magnetometers) do not show any coinciding Pc1 events. Therefore, our speculation on the association of this event with the Pc1 geomagnetic pulsation is based on indirect evidence. First, the AKR pulsation frequencies (1.2 to 4.0 Hz) are well within the range of geomagnetic pulsations (0.2–5 Hz). Second, the propagation of AKR sources is in agreement with a downward propagation of the Pc1 waves [*Erlandson et al.*, 1990, 1996]. Third, as it has already been mentioned, the apparent speeds of AKR sources are typical for the parallel speeds of Alfvén waves in the auroral cavity. Fourth, Pc1 geomagnetic pulsations occur most often during the recovery phase of magnetic storms [*Heacock and Kivinen*, 1972; *Bräysy and Mursula*, 1998; *Erlandson and Ukhorskiy*, 2001, and references therein]. Frequent occurrence of AKR pulsation events (14 cases) in the recovery phase of a magnetic storm on 16 May 2005 may suggest their association with Pc1 pulsations. In this interpretation the sporadic pulses with negative drifts can be related to the upgoing Pc1 waves reflected from the ionosphere.

[12] Some doubt on the association of AKR pulsations with geomagnetic Pc1 pulsations may arise from the fact that the Pc1 pulsations predominate on the dayside with occurrence maximum in the afternoon sector of local time [*Fraser and Nguyen*, 2001], while AKR predominates on the nightside with occurrence maximum in the evening sector [e.g., *Gurnett*, 1974; *Hanasz et al.*, 2003; *Green et al.*, 2004]. According to *Green et al.* [2004] in winter time the region of AKR occurrence broadens up to ~18 to 24 h MLT due to tilt of the magnetic dipole away from the Sun. An example of Pc1 geomagnetic pulsation at 19 hours magnetic local time (MLT) provided by *Loto'aniu et al.* [2005, Figure 3b] clearly shows that the evening portion of the Pc1 pulsation occurrence region can overlap with the winter region of AKR occurrence for events of June 2003 and May 2005. This, together with Pc1 association with magnetic storms, may explain why the AKR pulsations at Pc1 frequencies occur so rarely.

[13] *Bräysy and Mursula* [1998] have established that Pc1 waves originate in the remote equatorial regions of the magnetosphere as electromagnetic ion cyclotron waves. They propagate earthward along magnetic field lines from the distant sources as Alfvén waves since their frequencies are below all of the local ion gyrofrequencies everywhere along the path [*Lund et al.*, 1995], and convert into inertial waves in the auroral cavity. Another possibility is that the electromagnetic ion cyclotron waves suggested by observations of flickering aurora [*McFadden et al.*, 1987] (which originate in the auroral region), modulate the field aligned component of the electron flux at a wave frequency

[*Temerin et al.*, 1986]. Whatever the wave origin is, we assume in our scenario that some waves at Pc1 frequencies are present in the auroral cavity at altitudes of 11,500 to 13,500 km. These waves can periodically accelerate electrons on auroral field lines to energies of several keV and modify the 'shell' electron distribution in the converging magnetic field, which is needed for generation of pulsating AKR through the electron cyclotron maser instability.

[14] In this paper we describe AKR pulsations at Pc1 frequencies and provide indirect evidence that they are induced by the Pc1 geomagnetic pulsations. The paper enhances the significance of inertial Alfvén waves in the transient formation of unstable electron distributions capable of generating pulsating AKR. It is not contrary to the significance of quasi-stationary electric fields for continuously restoring unstable electron distributions, which subsequently are stabilized by generation of the 'typical' AKR. Future work should consist of a search for more cases of AKR pulsations at Pc1 frequencies and simulations of the proposed scenario.

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